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APPLICATION OF ANALYTICAL TECHNIQUES TO FLIGHT EVALUATIONS IN CRITICAL CONTROL AREAS

by

J. WEIL

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(6) APPLICATION OF ANALYTICAL TECHNIQUES TO FLIGHT EVALUATIONS IN CRITICAL CONTROL AREAS,

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Joseph Weil,

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SUMMARY

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The Report considers basic stability problems such as pitch-up, roll coupling, and marginal directional stability. Development of augmentation systems and control system evaluations are also discussed in some detail. Throughout the Report, the importance of co-ordinating flight and similar results are very much stressed and it is shown that in many areas even the most painstaking interpretation of flight data can lead to possible disaster if flight tests are not adequately supported by simulator studies using realistic stability and control derivatives.

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NOTATION

a_n	normal acceleration, g units
a_t	transerve acceleration, g units
b	wing span, ft
C_l	rolling-moment coefficient, rolling moment/$\bar{q}Sb$
C_{l_β}	effective dihedral derivative, $\partial C_l/\partial_\beta$
$C_{l_{\delta_a}}$	$= \partial C_l/\partial \delta_a$, per dag
C_m	pitching-moment coefficient, pitching moment/$\bar{q}S\bar{c}$
C_{m_α}	longitudinal-stability derivative, $\partial C_m/\partial\alpha$, per deg
$C_{m_{\delta_h}}$	$= \partial C_m/\partial\delta_h$ per deg
C_N	normal-force coefficient, normal force/$\bar{q}S$
C_{N_α}	normal-force-curve slope, $\partial C_N/\partial\alpha$, per deg
C_n	yawing-moment coefficient, yawing moment/$\bar{q}Sb$
C_{n_β}	directional-stability derivative, $\partial C_n/\partial\beta$, per deg
$C_{n_{\delta_a}}$	$= \partial C_n/\partial\delta_a$ per deg
$C_{n_{\delta_v}}$	vertical-tail-effectiveness parameter
$\bar{c}$	mean aerodynamic chord, ft
F	stick force, lb
g	acceleration of gravity, 32.2 ft/sec^2
h_p	pressure altitude, ft
I_X	moment of inertia about X-axis, slug ft^2
I_{X_e}	moment of inertia of rotating mass of the engine relative to its axis of rotation, slug-ft^2
I_Y	moment of inertia about Y-axis, slug-ft^2
I_Z	moment of inertia about Z-axis, slug ft^2
i_t	stabilizer incidence, deg

L	rolling moment/I_X , per sec^2
M	Mach number
N	yawing moment/I_Z , per sec^2
p	rolling angular velocity, deg/sec or radians/sec
$\bar{p}$	average rolling velocity, radians/sec
$\bar{p}_{cr}$	critical rolling velocity (see Fig. 5)
q	pitching angular velocity, radians/sec
$\bar{q}$	dynamic pressure, $\frac{1}{2}\rho V^2$, lb/ft^2
r	yawing angular velocity, radians/sec
S	wing area, ft^2
t	time, sec
V	airspeed, ft/sec
α	angule of attack, deg
αp	maximum positive or negative angle of attack attained in a roll maneuver, deg
α_0	angle of attack of principal axis, radians
α_1	initial angle of attack, deg
β	angle of sideslip, deg
β_{max}	maximum angle of sideslip, deg
$\Delta\phi$	incremental change in bank angle, deg
δ	control-surface deflection, deg or radians
δ_a	aileron deflection, positive when left aileron is deflected down, deg
δ_{a_L}	left-aileron deflection, deg
δ_{a_R}	right-aileron deflection, deg
δ_{a_t}	total aileron deflection, deg
δ_e	elevator deflection, positive when trailing edge down, deg

δ_h	horizontal-stabilizer deflection, positive when trailing edge down, deg
δ_r	rudder deflection, positive when deflected to left, deg
δ_{YD}	yaw-damper deflection, deg
$\dot{\theta}$	pitching velocity, deg/sec
ρ	mass density of air, slug-ft^3
ϕ	angle of bank, deg
ω_e	rotational velocity of engine rotor, radians/sec
ω_n	undamped natural frequency of Dutch roll mode, radians/sec

Subscripts

The subscripts β and δ_a indicate the partial derivative with respect to the specific subscript.

APPLICATION OF ANALYTICAL TECHNIQUES TO FLIGHT EVALUATIONS IN CRITICAL CONTROL AREAS

Joseph Weil*

1. INTRODUCTION

Since its inception in 1947, the Flight Research Center of the N.A.S.A. has engaged in a wide range of basic stability and control research using a variety of rocket and jet aircraft as test vehicles. Some of the general objectives of these many flight investigations are summarized below.

General Objectives of Flight-Test Programs
1. To conduct exploratory stability and control programs in a flight environment
2. To correlate flight results with predictions
3. To determine whether safe to proceed to more critical condition (flight guidance)
4. To determine criteria against which other aircraft can be evaluated
5. To determine whether a specific aircraft meets detailed handling-quality requirements

Because the N.A.S.A. Flight Research Center has been concerned mainly with exploratory investigations of flight-control problems, most emphasis has been placed on the first three items. The Flight Research Center methods may differ somewhat from the procedures an aircraft company might use in demonstrating and certifying a new design. Nevertheless the pitfalls encountered and the ultimate solutions to the problems should be of general interest.

Since the scope of this subject is so broad and the approaches are many, this Report is limited to studies of inertia coupling, lateral-directional control problems, and pitch-up.

Three flight-test situations are discussed. In one, the phenomenon is more or less unexpected and, perhaps, unknown; therefore, all analysis is necessarily after the fact. In the second, an in-flight build-up procedure is used - however, without adequate supporting analytical work. Finally, the procedure by which flight-test and analytical work are closely co-ordinated is described.

2. ROLL COUPLING

In 1954, the first flight experience with inertial coupling in rolling maneuvers was encountered. Prior to this time, published reports of analytical studies[1] pre-

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dicted the existance of the problem area. Unfortunately, the predictions were, for the most part, treated as an academic curiosity until the jarring realization of an actual occurrence in flight.

A chronological examination of the experiences of the Flight Research Center pertinent to roll coupling during the period from 1954 to 1958 provides an excellent illustration of the three types of situations referred to in Section 1.

2.1 F-100A

The first manifestations of serious roll coupling at the Flight Research Center occurred almost simultaneously on the X-3 and F-100A airplanes in late 1954. Because the F-100 was a military aircraft just entering operational squadrons, there was a tremendous push by both military and civilian officials to obtain a complete understanding of the causes of the violent and uncontrollable motions at the earliest possible date. Essentially all Flight Research Center effort was, therefore, concentrated on obtaining solutions of the F-100 problem.

The first indication of severe roll coupling encountered on the F-100A airplane at the Flight Research Center is shown in Figure 1. This is a time history of an abrupt two-thirds-aileron-deflection roll to the left made from level flight at a Mach number of 0.70 and an altitude of 32,000 feet. This roll occurred, incidentally, during the first series of planned roll maneuvers. Unfortunately, the roll-velocity trace was lost during the maneuver. Sone after the aileron-control input, angle of attack decreased steadily and negative (adverse) sideslip developed. Between 3 and 4 seconds, the rates of divergence in angles of attack and sideslip increased markedly and the maneuver became uncontrollable. Recovery was made when the controls were brought close to their initial settings. During the motion, a left sideslip angle of 26^{o} was recorded and angles of attack much larger than -16^{o} were attained, followed by 12^{o} at recovery. The large excursions encountered were similar to those which had been measured months earlier during some North American Aviation flight tests.

There were many theories concerning the cause of the coupled motions. These ranged from the realization that, in fact, roll coupling had been encountered, to assumptions of longitudinal instability at low angles of attack, large effects of pitching moment due to sideslip, and static-directional instability. Immediate steps were taken by personnel of the Flight Research Center and Langley Research Center to analyze the violent manuever on the analog. A five-degree-of-freedom form of the equations of motion was used, which included cross-coupling terms and the best available stability and control derivatives. Some of the required derivatives were obtained from an expedited low-speed wind-tunnel test program conducted at the Langley Research Center following the manuever shown in Figure 1.

A comparison of the calculated motions with flight data is presented in Figure 2. Although the exact phasing of the motion could be improved, the basic correlation was fairly good. Thus, it was established clearly and for the first time that the violent motions were caused by roll coupling and could be estimated to a good degree of accuracy.

During the same analog program, various controlling parameters such as C_{n_β}, C_{m_α} and $C_{n_{\delta_a}}$ were caried in a systematic fashion. These tests indicated that the major cause of severe roll coupling in the F-100A was insufficient directional stability. The sensitivity of the motions to small stabilizer inputs and the beneficial effects of increased pitch damping were also clearly revealed.

The analog results made it possible to proceed, with some confidence, with roll evaluations of the F-100 using two enlarged vertical tails provided by North American Aviation. Even so, the flight programs were conducted in a very cautious manner with initial rolls being made at low aileron deflections and restricted bank angles. No further occurrence of a completely divergent maneuver was encountered on the F-100, although sideslip angles as high as 20° were reached with the intermediate tail. The larger tail tested was adopted for the production versions of the F-100A and F-100C and has proved satisfactory even though sideslip angles of 14° or 15° are attainable in full-deflection 360° rolls at low dynamic pressure.

2.2 YF-102

At the same time that the F-100 roll integrity was being established, the Flight Research Center was also engaged in a general handling-quality evaluation program on the YF-102 airplane. Roll maneuvers were included in the program. Because of the F-100 and X-3 experiences with roll coupling, the roll program was planned in a gradual build-up fashion - however, without supporting analog tests. Low-deflection and short-duration rolls were attempted at first, followed by moderate-deflection 180° rolls. The latter rolls were accompanied by a moderate amount of sideslip but, as soon as the pilot applied corrective control, the airplane recovered immediately. The roll illustrated in Figure 3 was allowed to develop further than in the previous maneuver, with severe uncontrolled motions evident. Presented in Figure 3 are control deflections, rolling and pitching velocity, and angles of attack and sideslip. The results indicate a large increase in the rate of sideslip build-up at about 4 seconds ($\phi = 256°$). This caused the pilot to reverse the aileron control; however, appreciable rolling velocity was retained, and the sideslip build-up continued at an ever-increasing rate. At about 360° bank angle, the angle of attack suddenly diverged negatively, causing a large reinforcement of roll velocity. The up-elevator, applied at about 4 seconds, somewhat aggravated this maneuver. The pilot was unaware of the elevator input. He was, however, familiar with a similar maneuver previously encountered on the original F-100A airplane and personally had experienced several violent maneuvers on the X-3 airplane. In the instance of the F-100A, up-elevator had aggravated the motion. Recalling this, the pilot applied down-elevator at about the time of the angle-of-attack divergence ($t = 5$ sec). When this appeared to be of no avail, he pulled back on the stick and, although no quantitative data are available beyond $t = 7$ seconds, the controls were finally neutralized for recovery.

Immediate plans were made to conduct a detailed study of the problem on the analog - a step that should have been undertaken earlier. Figure 4 presents a comparison of the calculated and flight time histories, which show good correlation. The major aerodynamic derivatives used in the calculations were obtained from flight data. The only derivative not assumed constant with α was C_{l_β}. The exact simulation of a maneuver of this type can be critically dependent on small changes in many of the controlling parameters. The first attempts at correlation by using the flight derivatives resulted in maximum amplitudes of the same order as flight, but the phasing was rather poor. A minor reduction in the parameter $C_{n_{\delta_a}}$ produced the good agreement shown in Figure 4.

Although exact control inputs are used when attempting to correlate flight and calculated motions, general results of the type presented in Figure 5 for the YF-102 have proved to be of great value in flight planning as well as in giving a good indication of the relative severity of the roll-coupling problem.

Figure 5 summarizes the results of calculations for a series of 360° left rolls in which the operator used a control stick to stop the roll motion at about 360°. Presented are plots of aileron control angle, maximum sideslip angle, and maximum angle-of-attack excursions as a function of the average roll velocity in a roll maneuver. The average roll velocity was computed as the bank angle at control reversal divided by the time required to reach the specified bank angle. The vertical dashed line represents the lower undamped critical roll rate calculated by the formula shown. The value of $\bar{p}_{cr}$ depends on the static stability, inertia characteristics, and engine momentum. It was found in the general analog study of Reference 2 that the lower critical roll rate usually corresponded to the average roll rate at which near-maximum amplitudes occurred. The results shown in Figure 5 would predict the occurrence of maximum sideslip angles of the order of 26° and large angle-of-attack excursions, with the most extreme motions noted near critical roll rate. In the same roll range there is a break in the curve of δ_{a_t} plotted against $\bar{p}$ such that greatly different motions are attainable for essentially the same aileron deflection. The flight maneuver presented in the previous Figures is represented by the circular symbols. Although the control manipulation differed somewhat from that used in the general calculations, the maneuver occurred in a roll range where the more violent motions could be expected.

Although the exact control inputs (elevator as well as aileron) can play an important part in a specific roll maneuver, it is evident that simple general calculations of the type shown with elevator fixed would have indicated the intolerable nature of this flight condition had they been available at the proper time.

2.3 F-104A

As a result of initial Flight Research Center experience with severe roll coupling, it appeared that only a fully co-ordinated flight and analytical program could yield a safe approach for, in some instances, even the smallest incremental steps were not adequate flight safeguards.

In 1957, the N.A.C.A. was asked by the United States Air Force and Lockheed Aircraft Corporation to demonstrate the rolling capability of the F-104A airplane. Here was an opportunity to conduct a roll program in a systematic and rational fashion. Preliminary analog studies indicated that potentially serious problem areas existed at low and negative angles of attack.

A 35-flight program was completed in late 1957 in which the safe limits for rolling maneuvers were defined. By using the logic summarized in Figure 6 (discussed later), a large range of flight conditions was explored with dispatch without the occurrence of large excursions in angle of attack or sideslip or otherwise uncontrollable aspects. The correlation between estimated and flight results was generally good.

3. LATERAL-DIRECTIONAL PROBLEMS

Many aircraft have suffered over the years with a variety of lateral-directional-stability and control problems. This section will contrast the analysis techniques used for three representative occurrences.

3.1 F-104A Twin-Duct Instability

During the initial exploratory flight tests of the NACA F-104A airplane in January 1957, a compressor stall occurred at a Mach number of approximately 2.0 and an

altitude of 37,500 feet. Figure 7 shows a time history of the resulting motions. Immediately after the compressor stall, the throttle was retarded and shortly thereafter an undamped Dutch roll oscillation with an amplitude of about $\pm 4^{\circ}$ of sideslip was encountered. As the speed decreased to about $M = 1.5$, the motions finally subsided. Had this maneuver been performed at a somewhat lower altitude, the loads imposed on the vehicle might have been critical.

At first, it was thought that the lateral oscillation was sustained by aileron inputs caused by the lateral accelerations imposed on the pilot. Further analysis of wind-tunnel tests revealed that the disturbance producing the lateral oscillations was in the form of fluctuating asymmetric shock fields in the region of the twin inlets. Other wind-tunnel data and subsequent flight data indicated that at high Mach numbers under reduced throttle conditions, or following a compressor stall, the flow rates through each inlet and the accompanying shock positions differ. This produced a fuselage side force and yawing moment. The yawing moment caused the airplane to sideslip which, in turn, caused the shock position to reverse. A hysteresis-like model (Fig. 8) describing the disturbing moments was derived from the tunnel tests by Lockheed engineers.

The model was used with an analog at the Flight Research Center to assess the relative importance of a number of factors affecting the peak airplane motions attained during the forced lateral oscillations. The basic character of the flight motions was substantiated. It was found that the use of a relatively high yaw-damper gain produced both the deflection and rate saturation which rendered the yaw damper completely ineffective in the initial NASA flight experience. Later, flights with reduced damper gain and a 100% increase in the available yaw-damper rate produced a marked decrease in the motions obtained following intentional throttle retardation. The source of the problem was finally eliminated when the manufacturer modified the engine's operating characteristics and extended the splitter plate to within ½ inch of the compressor face, thus effectively isolating the two ducts.

The problem illustrated would, admittedly, have been difficult to predict. However, it is obvious that availability of suitable wind-tunnel data at an early date, together with the analytical means ultimately used, would have made it possible to assess the problem prior to flight.

3.2 X-2 Divergence

In September 1956 the X-2 airplane was lost after having attained a Mach number of 3.2. A time history obtained from records recovered from the wreckage is presented in Figure 9.

The analysis of the airplane instability experienced during the flight was made by using the internally recorded data, an analog computer, and the aerodynamic-derivative coefficients obtained from wind-tunnel and flight area. At the time of the last flight, the stability and control data available for flight guidance were limited to $M = 2.4$, although theoretical estimates were available for the ultimate Mach number range. A more complete set of wind-tunnel data was obtained following the accident to define the significant derivatives for the high angle-of-attack and Mach number region of the flight envelope, thereby enabling a more accurate analysis of the cause of the instability.

The directional instability shown in Figure 10 can be explained as follows: The X-2 remained stable up to a Mach number of 3.2 while at low angles of attack; however, after burnout, control motions were initiated to increase the angle of attack and to produce a left bank (see Fig. 11). As the speed decreased below $M \sim 3.0$ and the angle of attack simultaneously increased, the directional stability was lowered to such an extent that when right aileron was applied to stop the increasing left-bank angle, the yawing moment resulting from the aileron deflection caused a build-up in the right sideslip until the roll due to sideslip was greater than the maximum capability of the ailerons. Roll rate continued to build up rapidly until critical roll velocity for inertial coupling (calculated to be 1.35 radians per second for these conditions) was exceeded. At critical roll velocity, violent uncontrollable motions characteristic of inertial coupling, occurred about all three axes. It should be noted that the rudder was normally locked for flight at supersonic speed and there is no evidence that it was unlocked during the last X-2 flight.

A directional-stability analysis of two X-2 flights is hown in Figure 10. The directional-stability parameter C_{n_β} is seen to be positive during the last flight (B) at least until the divergence was well developed. However, when ailerons alone are used for control, the value of C_{n_β} required to maintain lateral control is equal to $C_{n_{\delta_a}} C_{l_\beta}/C_{l_{\delta_a}}$. On the lower portion of the figure a ratio of these parameters is plotted for two flights in a manner such that uncontrollability is present for values less than unity. Although a portion of an earlier flight (A) was in the Mach number range where an instability could occur, the airplane maintained a low angle of attack, with C_{n_β} always greater than the critical value. The ratio of C_{n_β} to the critical value for the last flight indicated that the airplane was unstable above a Mach number of 3.1, even though the angle of attack was low. Therefore, an instability before burnout could be expected; however, the divergence did not occur until approximately 15 seconds later when the angle of attack was higher and yawing moments resulting from control action were introduced. This indicates that the flight C_{n_β} was higher than wind-tunnel values, or that flight $C_{n_{\delta_a}}$ was lower than wind-tunnel values. A more complete discussion of the X-2 results can be found in Reference 3.

Figure 11 shows a time-history comparison of the directional divergence which occured during the last X-2 flight with a programed six-degree-of-freedom analog simulation of the divergence using modified derivatives obtained from the postflight wind-tunnel data. To obtain the agreement shown, it was necessary, as noted previously, to increase the value of C_{n_β} and to decrease the value of $C_{n_{\delta_a}}$ by small amounts.

The X-2 experience is an example of a flight program that was expanded too rapidly, considering the information available, to define adequately the projected flight regime. Although some simulator guidance was afforded the pilot prior to his fatal flight, it was obviously insufficient.

3.3 X-15 Damper-Off Lateral-Directional Instability

A Brief review of a recent study of a lateral-directional control problem involving the X-15 research airplane is presented in the following section. The discussion will illustrate a proper approach for investigating such problems.

The X-15 program has had, perhaps, the most complete and extensive wind-tunnel coverage ever available for an advanced vehicle. An important part of the flight program is to verify the wind-tunnel results and to have the best estimates available

The Report considers basic stability problems such as pitch-up, roll coupling, and marginal directional stability. Development of augmentation systems and control system evaluations are also discussed in some detail. Throughout the Report, the importance of co-ordinating flight and similar results are very much stressed and it is shown that in many areas even the most painstaking interpretation of flight data can lead to possible disaster if flight tests are not adequately supported by simulator studies using realistic stability and control derivatives.

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AGARD Report 369
North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development
APPLICATION OF ANALYTICAL TECHNIQUES TO FLIGHT EVALUATIONS IN CRITICAL CONTROL AREAS
Joseph Weil
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for flight planning. Figures 12 and 13 show comparisons of flight, wind-tunnel data, and theory for some of the more important stability and control parameters. As can be seen, the correlation is generally good. A complete discussion of the methods used in theoretical estimations is presented in Reference 4.

Each X-15 flight is planned in minute detail with the aid of a complete six-degree-of-freedom analog simulation. The simulator includes an almost exact replica of the X-15 cockpit and control-system hardware. In planning each flight, many possible emergency conditions are rehearsed by the pilots. In the Mach number range above 2.4, a large region of lateral-directional uncontrollability was found on the simulator for conditions with lateral-directional dampers inoperative.

To obtain flight verification, during several X-15 flights, pilots were instructed to attempt to stabilize the vehicle in the fringes of the uncontrollability region. A comparison of the estimated uncontrollable region and the small uncontrollable region thus far explored in flight is shown in Figure 14. The flight data indicate the problem to exist at a somewhat lower angle of attack then was estimated. A time history showing the aforementioned flight characteristics is presented in Figure 15 At time zero, the pilot switched off the lateral dampers. He attempted to stabilize the airplane but the motions tended to build up, so he reduced the angle of attack. The motions then rapidly subsided. A second pull-up maneuver was performed with the same results. The problem can be described as a pilot-airframe dynamic instability. The basic vehicle has essentially neutral damping with control surface fixed. However, when the pilot attempts to fly the airplane in the conventional manner by using ailerons to control bank angle, significant instability can be induced. A root-locus plot (Fig. 16) can be best to analyze the problem.

Figure 16 is a root-locus plot showing how the characteristics of the pilot-airplane combination change with pilot gain. Plotted are the real and the imaginary parts of the roots so that the right half plane (positive real part) must be void of roots for stability. The human transfer function used to represent the pilot consists of proportional plus derivative control (that is, $\delta_a = -5\phi - 2.9_p$) , which was developed in Reference 5. As the pilot's gain is increased, the roots of the Dutch roll mode immediately cross the right half plane, signifying a dynamically unstable mode. Had the ordinates of the complex zeros been less in magnitude than the complex poles, the path would not have entered the right half plane. A useful parameter, then, is the difference in the ordinates of these poles and zeros. The expression shown in the figure gives this difference, and is useful in explaining the effects of the pertinent aerodynamic and inertial characteristics. Additional information on problems of this nature may be found in Reference 6.

At present, the fixed-base simulator, the NASA F-100C variable-stability airplane, and the X-15 airplane are being used concurrently to develop alternate control techniques with dampers off to allow flight in an otherwise uncontrollable region should a critical damper failure occur.

4. PITCH-UP

The problem of pitch-up, or longitudinal instability, at moderate and high angles of attack has plagued airplane designers since low-aspect-ratio and swept-wing

aircraft were first introduced. Although the basic causes of pitch-up were well understood from analyses of countless wind-tunnel programs, it was often difficult and dangerous to attempt to obtain a clear picture of the extent of the problem from flight tests because of the dynamic nature of the maneuver and the sensitivity of the motions to piloting technique.

At the Flight Research Center, initial flight tests were always planned at high altitude, which greatly reduced the probability of exceeding structural load limits in the event of unexpected pitch-up. However, there was always the possibility of experiencing a pitch-up followed by an uncontrollable spin or directional divergence. Many of the early experiences with pitch-up were unexpected. Figure 17 illustrates a rather abrupt pitch-up encountered on the X-5 airplane. In this instance, at an angle of attack of approximately 18° the pitch-up is compounded by a violent directional divergence. Even in instances of milder pitch-up, it was often very difficult to analyze flight data quantitatively. The same problem existed in attempting to assess the effects of 'fixes' such as wing fences and chord extensions.

About 5 years after the first flight occurrence of pitch-up, digital and analog computers were first used to interpret wind-tunnel data in terms of time histories[7]. At about the same time, flight records were reduced to pitching-moment curves by accounting for pilot control inputs, inertia and damping effects. Correlation between wind-tunnel and flight data has, in general, been quite good and is typified by the comparison shown in Figure 18. This generally good correlation indicated that strong reliance could be placed on wind-tunnel data and estimated pitch-up time histories. Thus, comprehensive simulator studies or calculations are now usually made prior to flight tests in which moderate or strong pitch-up tendencies are anticipated.

The pitch-up region is often accompanied by separated flows; thus, there is another factor to consider when assessing the relative merits of configurational modifications which cannot be treated adequately in the usual simulator studies. This is illustrated by a flight evaluation, undertaken at the Flight Research Center in 1956, of the effect of slat span on the pitch-up characteristics of the F-100A airplane. The slats of the F-100A are composed of five free-floating, loosely connected segments. calculations based on wind-tunnel pitching-moment curves that had been made prior to flight tests indicated that locking the two inboard slats closed might result in minimizing pitch-up, which, incidentally, is rather mild on the F-100 airplanes. It was planned to investigate the effects of successively locking the slat segments, starting at the inboard end. The maneuvers performed consisted of wind-up turns with varying entry rate and recovery technique. In addition, clean-configuration and landing-configuration stalls were made for each configuration.

Figure 19 shows a comparison of the lift and pitching-moment characteristics obtained at $M = 0.88$ with all slats free to float, inboard section A locked, and the two inboard sections locked. Locking the inboard slat closed on each wing resulted in a milder initial pitch-up than with all slats free floating; however, mild lateral oscillations were evident just prior to the pitch-up. It is seen from Figure 19 that the pitching-moment characteristics were most stable at moderate angles of attack with sections A and B locked. However, in the opinion of the pilot, locking these two sections closed resulted in heavy buffet (note the break in the C_N curve) and produced 'wicked' longitudinal oscillations at moderate angles of attack. On occasion, unsymmetrical slat opening was accompanied by violent roll-offs. The motions

associated with this configuration tended to mask the pitch-up completely and were so objectionable that the only other configuration tested was with all slats closed.

A most significant conclusion derived from this study is that estimated effects of configurational changes on pitch-up severity which neglect concommitant stall phenomena can be completely unrealistic.

For some supersonic airplane designs, performance or structural considerations might dictate the use of design features, such as a high horizontal tail, which are susceptible to pitch up at high angle of attack. In such instances, one logical approach is to provide means of preventing the pilot from attaining flight conditions that could lead to possible disaster.

Air Force flight evaluations indicated that the F-104A airplane had a serious pitch-up problem. A simulator study was made at the Flight Research Center in which the controllability of the pitch-up, through the use of a stick pusher or a number of pitch-damper configurations, or both, was investigated. A schematic drawing of the test set-up is shown in Figure 20. A torque servo was used in conjunction with a control stick to provide stick force. Pull-up maneuvers were performed at various entry rates, with the pilot using a scope presentation of angle of attack to close the simulation loop. A number of NASA and Air Force pilots operated the simulator and operated the simulator and were favorably impressed with the realism afforded by the simple presentation.

For the configuration without the stick pusher, a moderate-authority pitch damper was greatly appreciated by the pilot when attempting to control the airplane below pitch-up and when trying to track in regions of neutral stability or limited instability. In even moderate-entry-rate pull-ups to instability, however, little tangible reduction in overshoot was realized from the pitch damper.

A series of tests was made to evaluate the relative importance of a number of design parameters which influence the design of a stick pusher. Typical stick-pusher-activation boundaries are shown in Figure 21. When the combined signals representing pitch rate and angle of attack exceed a boundary value, the stick pusher is activated and remains in operation until the sum of the parameters decreases below the specified boundary. The test technique used enabled an assessment of the individual and combined effects of such factors as stick-pusher boundary values (including the use of a washout circuit), pitch damping, and magnitude of stick-pusher force for various types of operations.

The effect of force level on the ability of the pilot to deliberately override the stick pusher is shown in Figure 22. The pilot was able to override only the 15 lb stick-pusher force. The 30 lb force provided positive and decisive action for preventing pitch-up. The highest force resulted in very high stabilizer rates and violent recovery transients.

The trends relating to stick-pusher operation and pitch-up formed in the simulator program correlated well with flight data. Thus, closed-loop simulation of similar devices to prevent pitch-up may be optimized on the simulator. This can result in minimization of flight development time.

4.1 Recommended Procedure

On the basis of the foregoing discussion, there appears to be a logical way of planning various types of flight investigations of critical stability and control problems. A typical example that was formulated to guide investigations of roll-coupling problems will now be described (see Fig. 6).

The first step involving preliminary analog studies to define the critical problem areas should be implemented during the design stage long before the flight-test program is initiated. These studies should be rechecked, however, prior to the beginning of a flight program. Derivatives obtained from wind-tunnel studies or theory, corrected for aeroelasticity, should be used. When the results of the initial calculations are available early in the design, it is assumed that necessary steps will be taken to insure that dangerous coupling would not exist in an important segment of the flight envelope.

Next, as early as possible in the actual flight test program, it is strongly recommended that as complete a determination as possible be made of stability and control derivatives from analysis of flight data. A check is thus furnished on the validity of the derivatives used in the preliminary calculations. This is important where there are large aeroelastic corrections or gaps in wind-tunnel data. A number of methods are adequate for determining the critical stability derivatives from pulses and sideslips. Frequently, the average value obtained from several methods has been utilized. The Flight Research Center has also been successful in obtaining the control parameters such as $C_{l_{\delta_a}}$, $C_{n_{\delta_a}}$ and $C_{m_{\delta_h}}$ from the initial angular acceleration following an abrupt control input[8].

After the flight derivatives have been obtained, representative flight conditions should be chosen and final roll calculations made for flight correlation. General computations of the type summarized in Figure 5 would appear to be ideal. In these general calculations the sensitivity to several degrees of inadvertent stabilizer input should be explored.

Next, a flight check of non-critical roll maneuvers should be made and compared with the calculated results. If the correlation is reasonably good, marginal maneuvers can be approached with some confidence in a gradual build-up technique.

A critical aileron deflection should always be checked, first at small bank angles; then, the bank angle may be increased in reasonable steps. Since it is believed that there is no sound reason to roll beyond 360°, Flight Research Center studies have been limited to this value. If unpredictable violent maneuvers develop, the pilot should neutralize all controls. The futility of trying to control such a motion was demonstrated earlier.

A question often raised in flight demonstrations of critical stability and control areas is: How close can the potentially dangerous area be approached? Unfortunately, this question has no simple answer. Many factors must be considered, such as the possibility of exceeding design loads and the availability of simple recovery techniques. Certainly, a potentially hazardous condition can be approached more closely and with a relatively higher degree of safety if the problem is well understood and techniques that can be used in emergencies are known - such as the use of stabilizer input to

terminate an autorotative condition. Actually, with careful planning, including adequate analog support, sufficient data can be obtained for correlation purposes without approaching too close to the precipice. Once adequate correlation between estimations and flight data has been established, full reliance should be placed on the analog results.

5. CONCLUDING REMARKS

During the past 7 years, an important evolution has occurred in the manner in which flight stability and control investigations are conducted. In the early part of the last decade, few analog or sophisticated analytical procedures were available by which complex dynamic motions could be predicted or reproduced following flight occurrence. Often, wind-tunnel data were rather meager and sketchy and flight control systems lacked even limited-authority damper augmentation. In this Report it has been shown that, individually or in combination, the aforementioned factors were responsible for many dangerous flight situations which, if not resulting in the loss of an aircraft, could materially lengthen development time.

At present, with the widespread availablity of analog and digital computers and adequate wind-tunnel derivative coverage, considerable knowledge of possible problem areas should be available with which to plan rational flight test programs. In addition, the trend toward stability augmentation systems should eliminate, or at least reduce, the severity of many inherent problem areas and facilitate controlled studies of potentially dangerous conditions in flight.

REFERENCES

1. Phillips, W.H. — *Effect of Steady Rolling on Longitudinal and Directional Stability.* NACA TN 1627, 1948.

2. Weil, J.; Day, R.E. — *An Analog Study of the Relative Importance of Various Factors Affecting Roll Coupling.* NACA RM H56A06, 1956.

3. Day, R.E.; Reisert, D. — *Flight Behavior of the X-2 Research Airplane to a Mach Number of 3.20 and a Geometric Altitude of 126,200 Feet.* NASA TM X-137, 1959.

4. Walker, H.J.; Wolowicz, C.H. — *Theoretical Stability Derivatives for the X-15 Research Airplane at Supersonic and Hypersonic Speeds Including a Comparison with Wind-Tunnel Results.* NASA TM X-287, 1960.

5. Taylor, L.W.; Day, R.E. — *Flight Controllability Limits and Related Human Transfer Functions as Determined from Simulator and Flight Tests.* NASA TN D-746, 1961.

6. Ashkenas, I.L.; McRuer, D.T. — *The Determination of Lateral Handling Quality Requirements from Airframe-Human Pilot System Studies.* WADC Tech. Rep. 59-135 (Contract No. AF 33(616)-5661), Wright Air Dev. Center, June 1959. (Available from ASTIA as AD 212 152.)

7. Campbell, G.S.; Weil, J. — *The Interpretation of Non-linear Pitching Moments in Relation to the Pitch-Up Problem.* NASA TN D-193, 1959. (Supersedes RM L53102.)

8. Wolowicz, C.H.; Holleman, E.C. — *Stability-Derivative Determination from Flight Data.* AGARD Rep. 224, 1958. (Presented at Thirteenth Meeting of the Flight Test Panel, Copenhagen, Denmark, Oct. 20 to 25, 1958.)

BIBLIOGRAPHY

Finch, T.W.
Walker, J.A.
Flight Determination of the Static Longitudinal Stability Boundaries of the Bell X-5 Research Airplane with 59° Sweepback. NACA RM L53A09b, 1953.

Fischel, J.
Nugent, J.
Flight Determination of the Longitudinal Stability in Accelerated Maneuvers at Transonic Speeds for the Douglas D-558-II Research Airplane Including the Effects of an Outboard Wing Fence. NACA RM L53A16, 1953.

Sisk, T.R.
Mooney, J.M.
Preliminary Measurements of Static Longitudinal Stability Trim for the XF-92A Delta-Wing Research Airplane in Subsonic and Transonic Flight. NACA RM L53B06, 1953.

Holleman, E.C.
et alii
Preliminary Flight Measurements of the Dynamic Longitudinal Stability Characteristics of the Convair XF-92A Delta-Wing Airplane. NACA RM L53E14, 1953.

Day, R.E.
Measurements Obtained During the Glide-Flight Program of the Bell X-2 Research Airplane. NACA RM L53G03a, 1953.

Ankenbruck, H.O.
Determination of Longitudinal Stability in Supersonic Accelerated Maneuvers for the Douglas D-558-II Research Airplane. NACA RM L53J20, 1954.

Fischel, J.
Effect of Wing Slats and Inboard Wing Fences on the Longitudinal Stability Characteristics of the Douglas D-558-II Research Airplane in Accelerated Maneuvers at Subsonic and Transonic Speeds. NACA RM L53L16, 1954.

Sadoff, M.
Crossfield, A.S.
A Flight Evaluation of the Stability and Control of the X-4 Swept-Wing Semitailless Airplane. NACA RM H54G16, 1954.

Ankenbruck, H.O.
Determination of Longitudinal Handling Qualities of the D-558-II Research Airplane at Transonic and Supersonic Speeds to a Mach Number of about 2.0. NACA RM H54G29a, 1954.

Fischel, J.
Brunn, C.D.
Longitudinal Stability Characteristics in Accelerated Maneuvers at Subsonic and Transonic Speeds of the Douglas D-558-II Research Airplane Equipped with a Leading-Edge Wing Chord-Extension. NACA RM H54H16, 1954.

Ankenbruck, H.O.
Wolowicz, C.H.
Lateral Motions Encountered with the Douglas D-588-II All-Rocket Research Airplane During Exploratory Flights to a Mach Number of 2.0. NACA RM H54I27, 1954.

Holleman, E.C.
Triplett, W.C. — *Flight Measurements of the Dynamic Longitudinal Stability and Frequency-Response Characteristics of the XF-92A Delta-Wing Airplane.* NACA RM H54J26a, 1955.

Sisk, T.R.
Muhleman, D.O. — *Longitudinal Stability Characteristics in Maneuvering Flight of the Convair XF-92A Delta-Wing Airplane Including the Effects of Wing Fences.* NACA RM H54J27, 1955.

N.A.C.A. — *Flight Experience with Two High-Speed Airplanes Having Violent Lateral-Longitudinal Coupling in Aileron Rolls.* NACA RM H55A13, 1955.

Sisk, T.R.
Muhleman, D.O. — *Lateral Stability and Control Characteristics of the Convair XF-92A Delta-Wing Airplane as Measured in Flight.* NACA RM H55A17, 1955.

Finch, T.W. — *Flight Determination of the Longitudinal Stability and Control Characteristics of the Bell X-5 Research Airplane at 58.7° Sweepback.* NACA RM H55C07, 1955.

Day, R.E.
Fischel, J. — *Stability and Control Characteristics Obtained During Demonstration of the Douglas X-3 Research Airplane.* NACA RM H55E16, 1955.

Weil, J.
et alii — *Flight Experience of Inertia Coupling in Rolling Maneuvers.* NACA RM H55E17b, 1955.

Holleman, E.C. — *Flight Measurements of the Lateral Response Characteristics of the Convair XF-92A Delta-Wing Airplane.* NACA RM H55E26, 1955.

Fischel, J.
Reisert, D. — *Effect of Several Wing Modifications on the Low-Speed Stalling Characteristics of the Douglas D-558-II Research Airplane.* NACA RM H55E31a, 1955.

Drake, H.M.
Stillwell, W.H. — *Behavior of the Bell X-1A Research Airplane During Exploratory Flights at Mach Numbers Near 2.0 and at Extreme Altitudes.* NACA RM H55G25, 1955.

Drake, H.M.
et alii — *Flight Measurements of Directional Stability to a Mach Number of 1.48 for an Airplane Tested With Three Different Vertical Tail Configurations.* NACA RM H55G25, 1955.

Sisk, T.R.
Andrews, W.H. — *Flight Experience with a Delta-Wing Airplane Having Violent Lateral-Longitudinal Coupling in Aileron Rolls.* NACA RM H55H03, 1955.

Videan, E.N. — *Flight Measurements of the Dynamic Lateral and Longitudinal Stability of the Bell X-5 Research Airplane at 58.7° Sweepback.* NACA RM H55H10, 1955.

Finch, T.W. et alii	*Flight Investigation of the Effect of Vertical-Tail Size on the Rolling Behavior of a Swept-Wing Airplane Having Lateral-Longitudinal Coupling.* NACA RM H55L28a, 1956.
Williams, W.C. et alii	*Comparison of Flight and Wind-Tunnel Measurements of High-Speed-Airplane Stability and Control Characteristics.* NACA TN 3859, 1956.
Weil, J. Day, R.E.	*An analog Study of the Relative Importance of Various Factors Affecting Roll Coupling.* NACA RM H56A06, 1956.
Wolowicz, C.H.	*Time-Vector Determined Lateral Derivatives of a Swept-Wing Fighter-Type Airplane with Three Different Vertical Tails at Mach Numbers Between 0.70 and 1.48.* NACA RM H56C20, 1956.
Weil, J. Day, R.E.	*Correlation of Flight and Analog Investigations of Roll Coupling.* NACA RM H56F08, 1956.
Sisk, T.R. et alii	*Flight Evaluation of the Lateral Stability and Control Characteristics of the Convair YF-102 Airplane.* NACA RM H56G11, 1957.
Wolowicz, C.H.	*Dynamic Longitudinal Stability Characteristics of a Swept-Wing Fighter-Type Airplane at Mach Numbers Between 0.36 and 1.45.* NACA RM H56H03, 1957.
Andrews, W.H. et alii	*Longitudinal Stability Characteristics of the Convair YF-102 Airplane Determined from Flight Tests.* NACA RM H56I17, 1956.
Matranga, G.J. Peele, J.R.	*Flight-Determined Static Lateral Stability and Control Characteristics of a Swept-Wing Flighter Airplane to a Mach Number of 1.39.* NACA RM H57A16, 1957.
Wolowicz, C.H. Rediess, H.A.	*Effects of Jet Exhausts on Flight-Determined Longitudinal and Lateral Dynamic Stability Characteristics of the Douglas D-558-II Research Airplane.* NACA RM H57G09, 1957.
Fischel, J. et alii	*Effects of Wing-Mounted External Stores on the Longitudinal and Lateral Handling Qualities of the Douglas D-558-II Research Airplane.* NACA RM H57H12, 1957.
Fishchel, J. et alii	*Flight Investigation of the Transonic Longitudinal and Lateral Handling Qualities of the Douglas X-3 Research Airplane.* NACA RM H57105, 1957.
Holleman, E.C. Boslaugh, D.L.	*A Simulator Investigation of Factors Affecting the Design and Utilization of a Stick Pusher for the Prevention of Airplane Pitch-Up.* NACA RM H57J30, 1958.

Matranga, G.J.
Armistead, K.H.

Flight Evaluation of the Effects of Leading-Edge-Slat Span on the Stability and Control Characteristics of a Swept-Wing Flighter-Type Airplane During Accelerated Longitudinal Maneuvers at Transonic Speeds. NACA RM H58A03a, 1958.

Matranga, G.J.

Roll Utilization of an F-100A Airplane During Service Operational Flying. NASA MEMO 12-1-58H, 1959.

Andrews, W.H.
Rediess, H.A.

Flight-Determined Stability and Control Derivatives of a Supersonic Airplane with a Low-Aspect-Ratio Unswept Wing and a Tee-Tail. NASA MEMO 2-2-59H, 1959.

Finch, T.W.
Matranga, G.J.

Launch, Low-Speed, and Landing Characteristics Determined from the First Flight of the North American X-15 Research Airplane. NASA TM X-195, 1959.

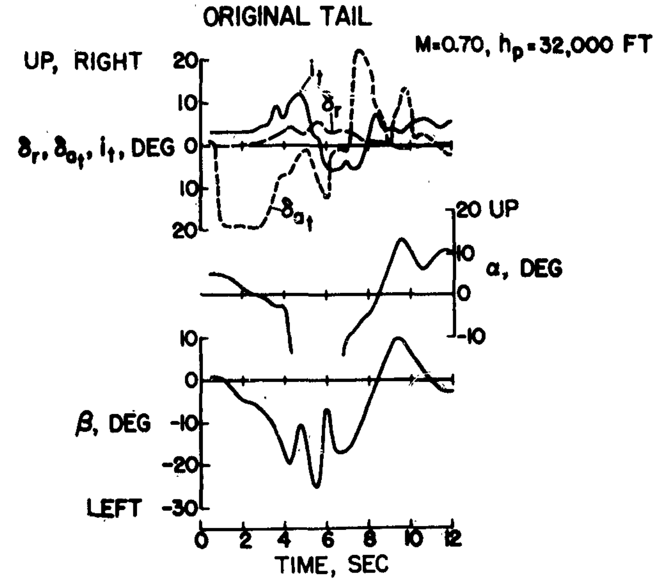

Fig. 1 Flight time history of F-100A aileron roll

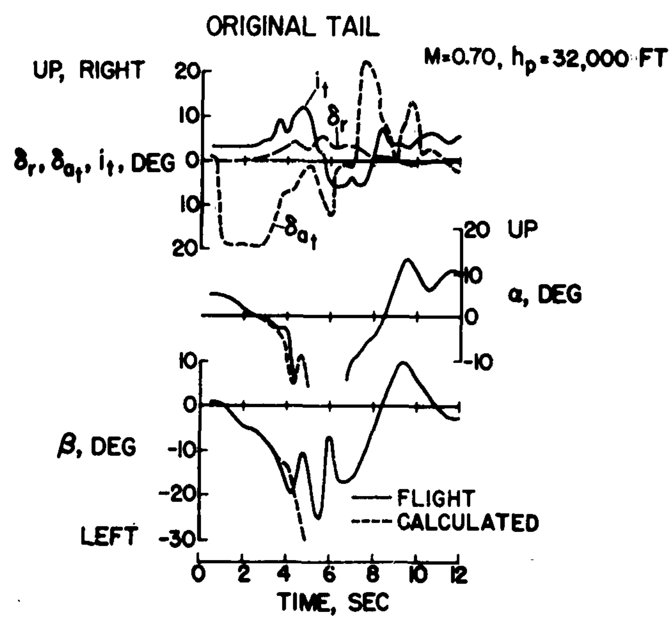

Fig. 2 Comparison between F-100A flight and calculated roll

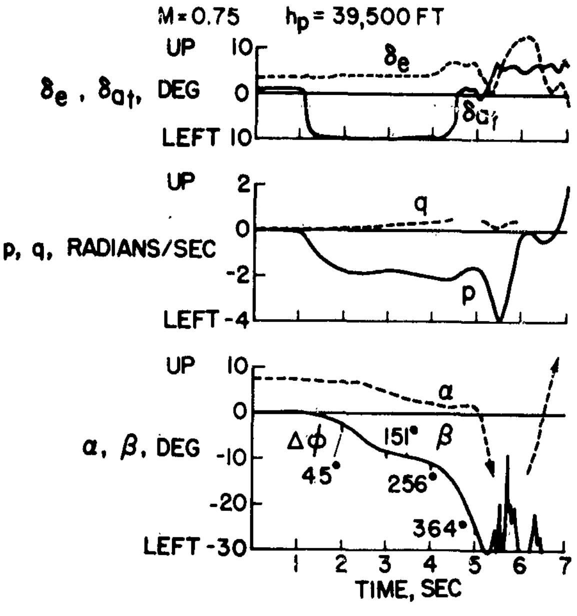

Fig. 3 Time history of abrupt YF-102 aileron roll

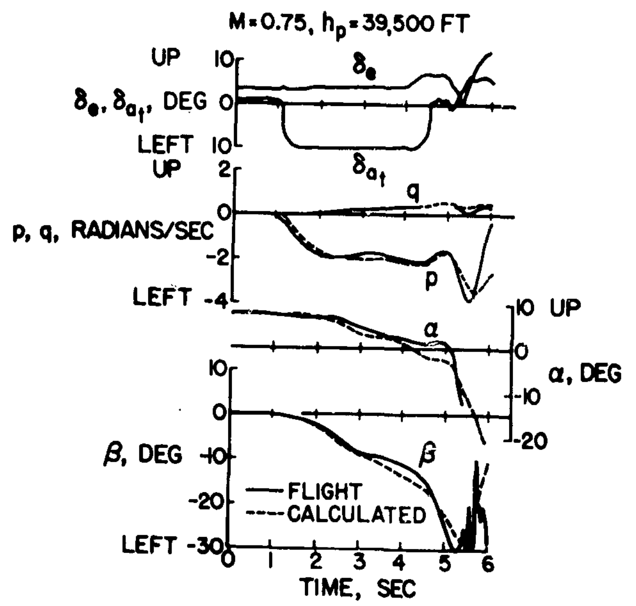

Fig. 4 Comparison between YF-102 flight and calculated roll

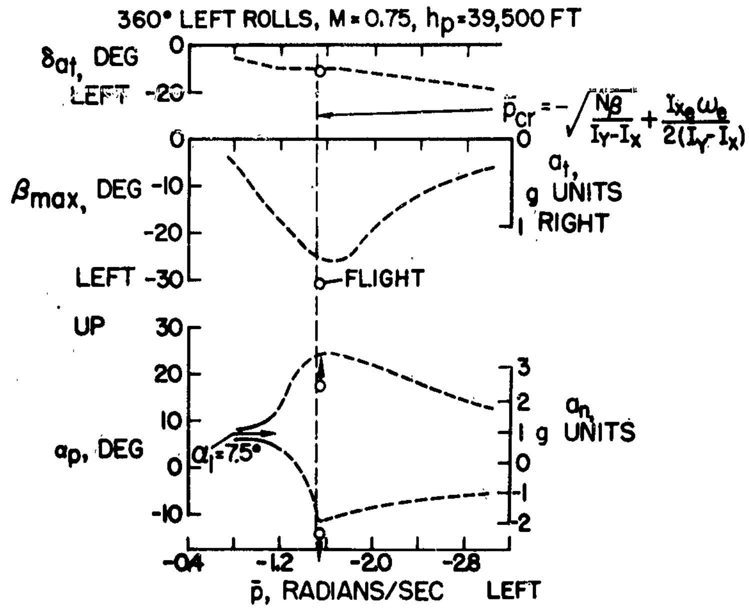

Fig. 5 Calculated YF-102 roll characteristics

1. PREFLIGHT CALCULATIONS TO DETERMINE CRITICAL AREAS
2. FLIGHT DETERMINATION OF STABILITY AND CONTROL DERIVATIVES
3. FINAL ROLL CALCULATIONS FOR FLIGHT CORRELATION
4. FLIGHT CHECK OF NONCRITICAL ROLLS
5. GRADUAL BUILDUP TO CRITICAL CONDITIONS

Fig. 6 Logical steps in roll-coupling flight program

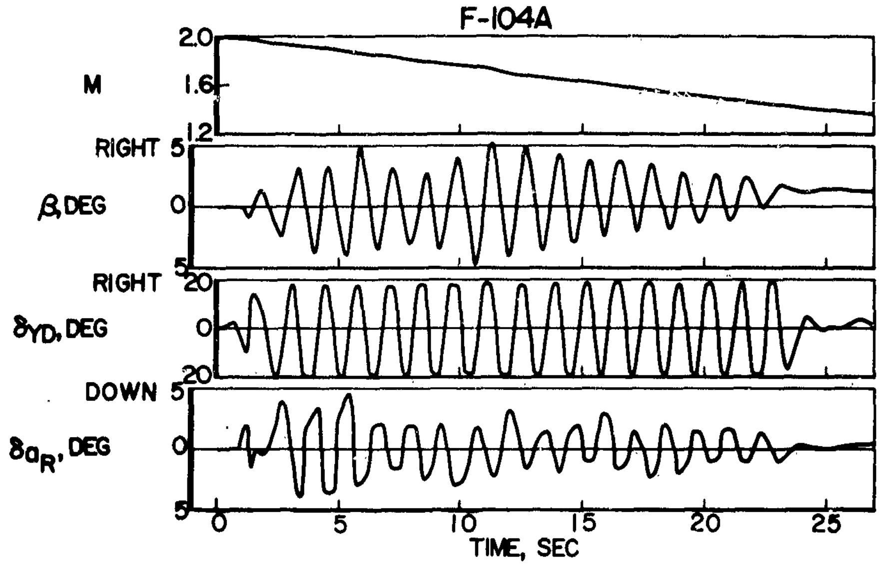

Fig. 7 Lateral motions caused by twin-inlet instability

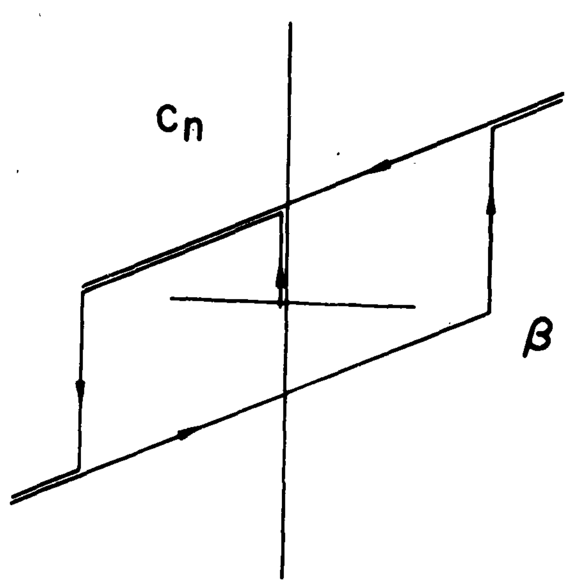

Fig. 8 Model used to describe F-104 twin-duct-instability forcing functions

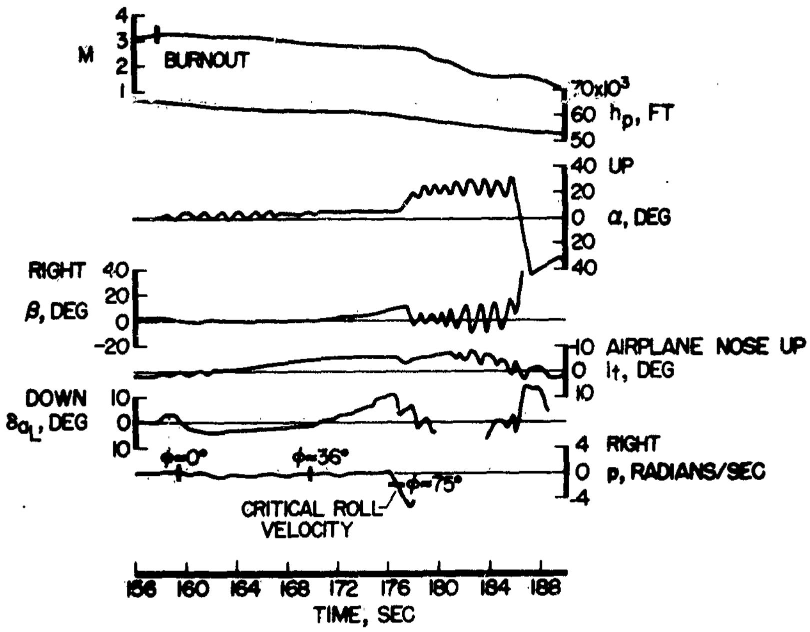

Fig. 9 High mach number behavior of X-2

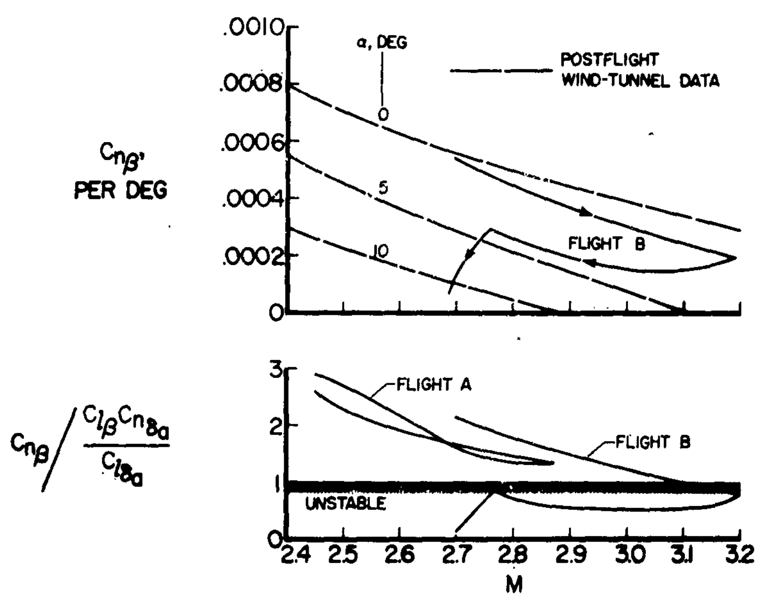

Fig. 10 X-2 directional-stability analysis

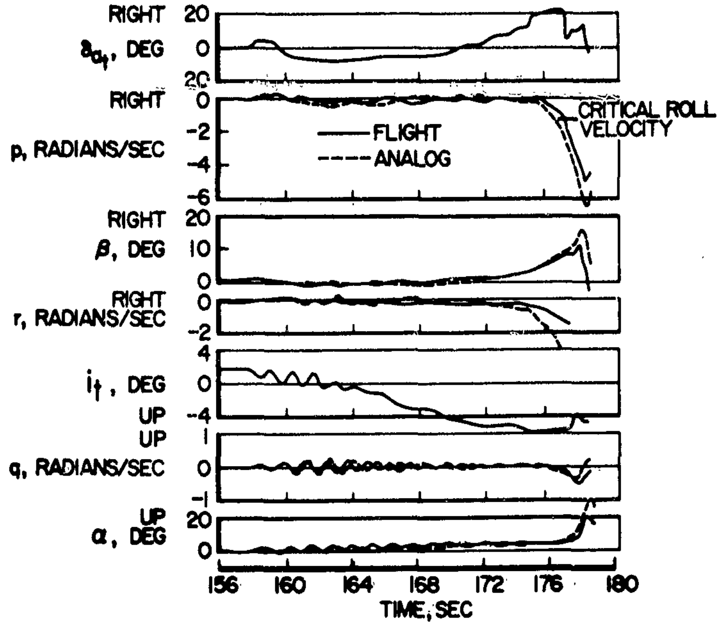

Fig. 11 Flight and calculated X-2 motions

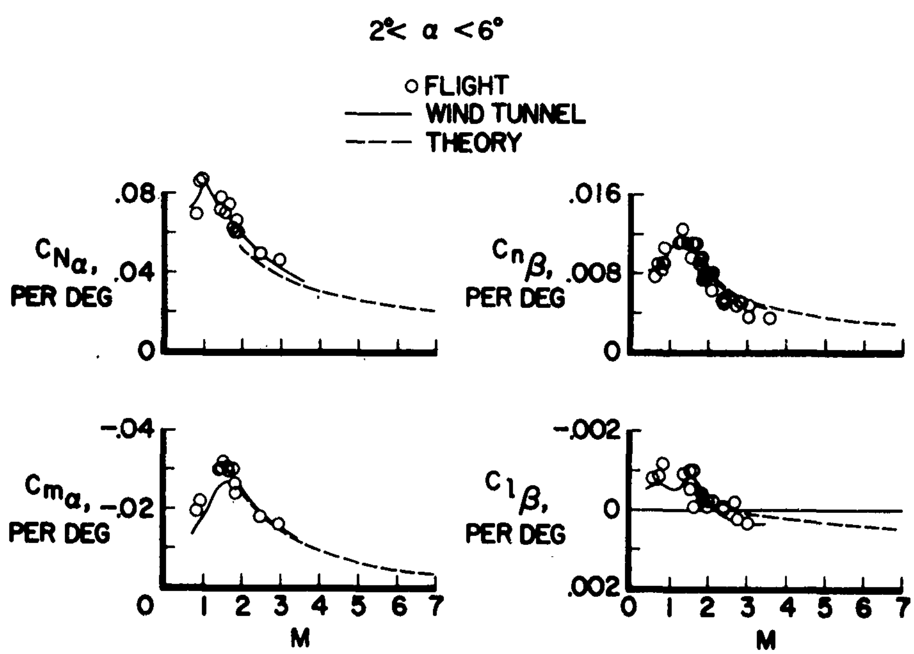

Fig. 12 X-15 stability derivatives

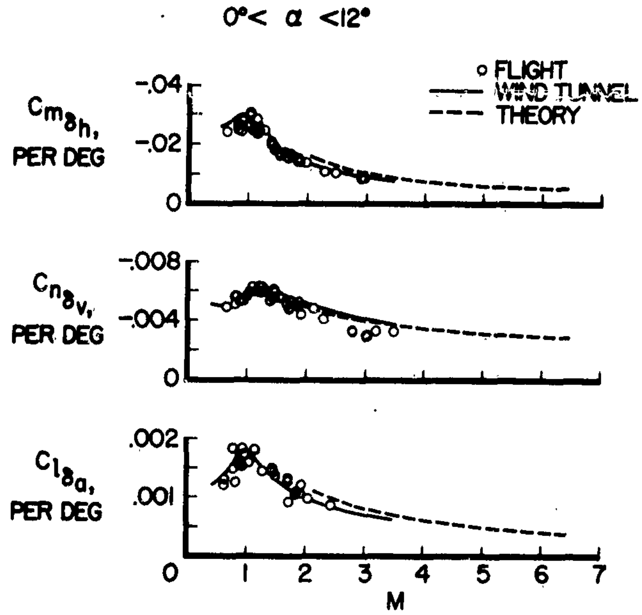

Fig. 13 X-15 control effectiveness derivatives

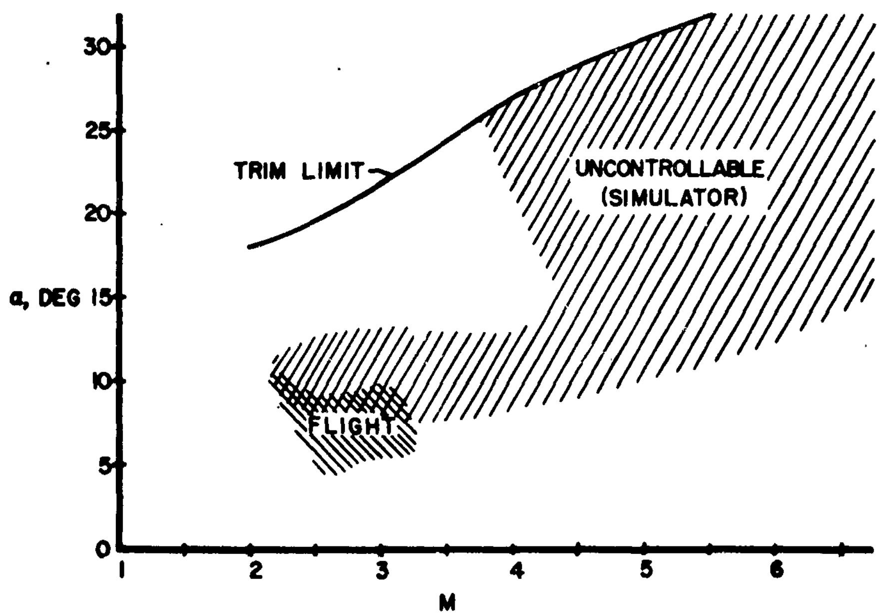

Fig. 14 X-15 dampers-off control boundary

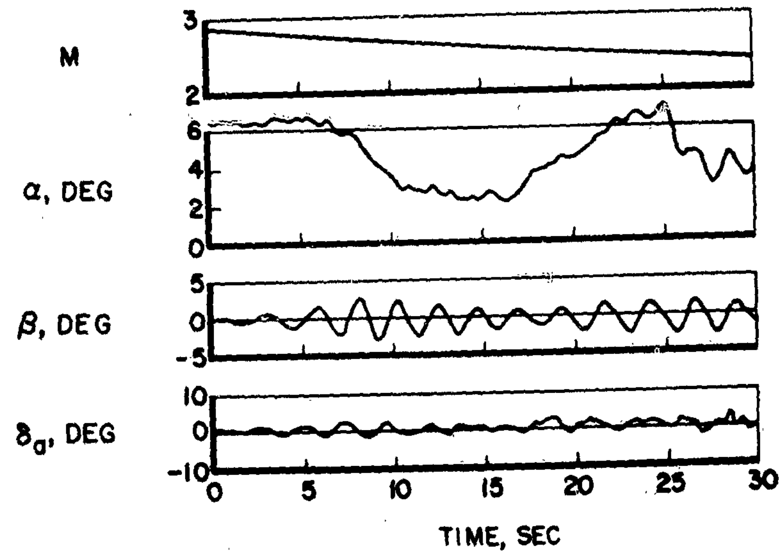

Fig. 15 X-15 control divergence

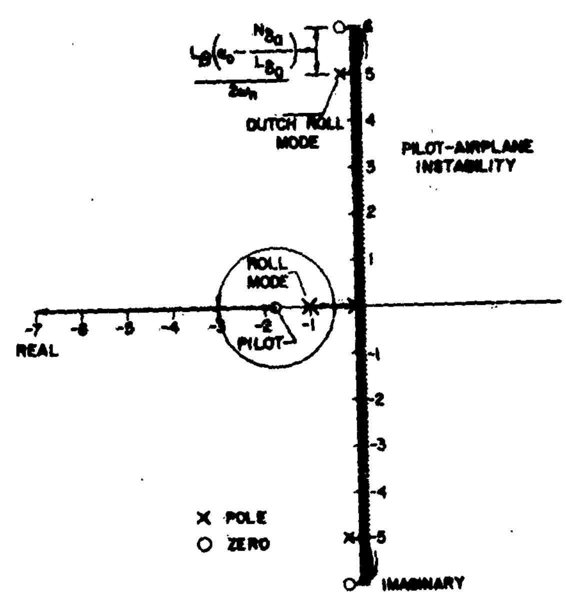

Fig. 16 Use of root locus to explain pilot-aircraft instability

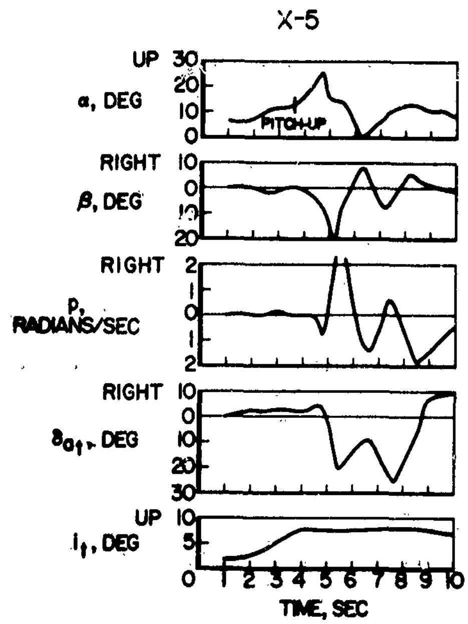

Fig. 17 Pitch-up followed by directional divergence

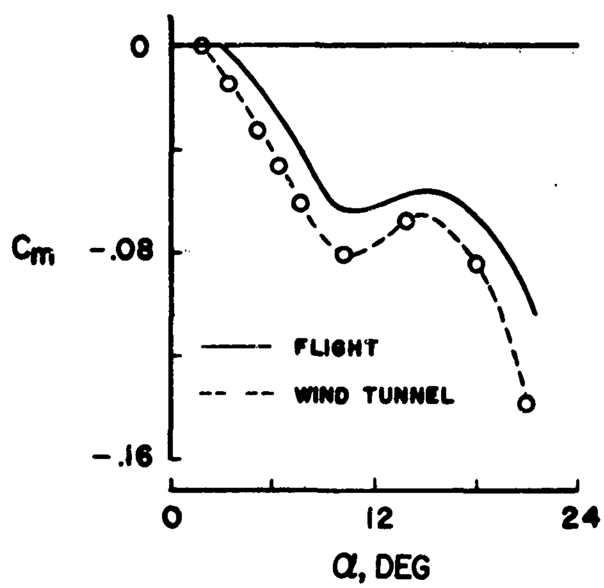

Fig. 18 Pitching-moment correlation

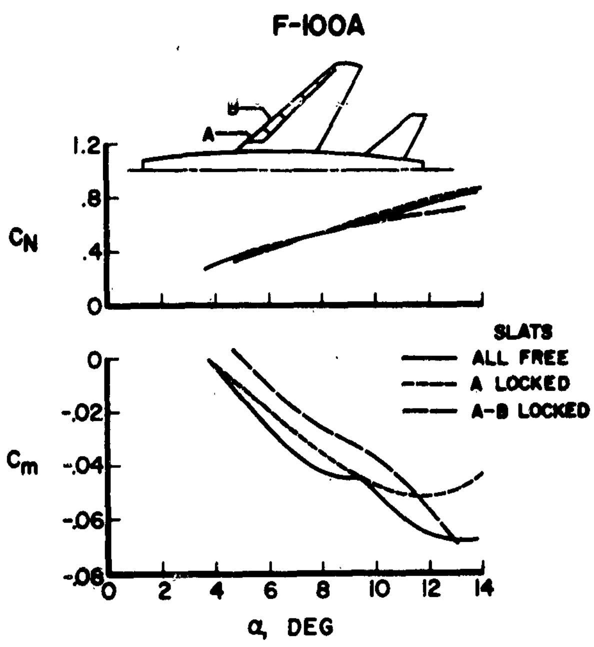

Fig. 19 Effect of slat span on pitch-up

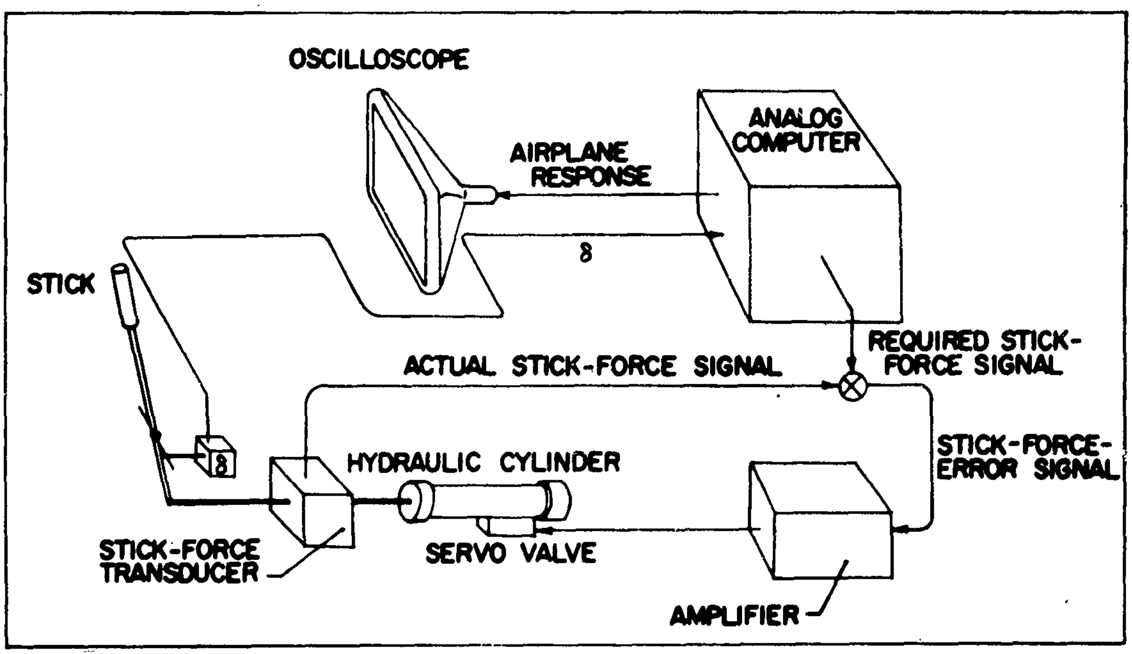

Fig. 20 Schematic diagram of pitch-up simulator

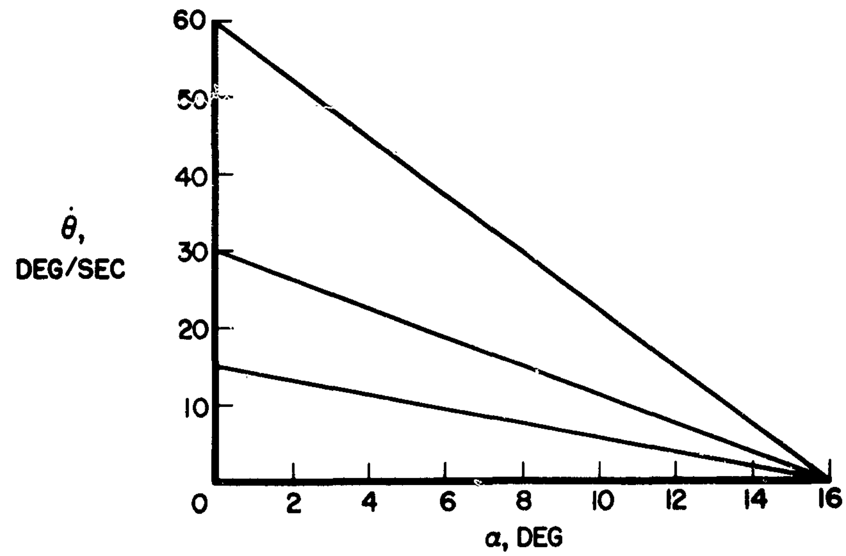

Fig. 21 Typical stick-pusher-activation boundaries

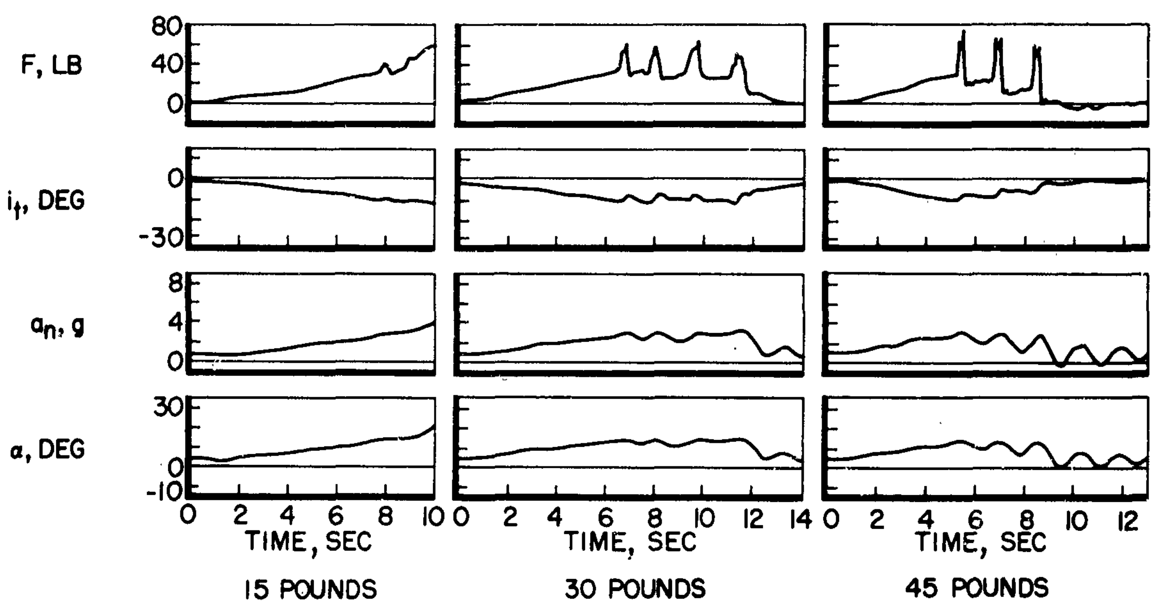

Fig. 22 Effect of stick-pusher-force level on pilot-override capability

DISCUSSION

H.J. Allwright (U.K.): I think it would be wrong for the discussion period to pass without a reference to this paper. I have no question to ask but consider Mr. Weil and the N.A.S.A. should be congratulated on this excellent and very honest exposition of the history and principles of flight evaluation in sensitive and potentially dangerous flight regions. They have emphasized that with new configurations and in new flight regions, complacency is out of order and that even apparently safe aircraft flight situations may catch us out.

ADDENDUM

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on

STABILITY AND CONTROL

Complete List of Papers Presented

Following is a list of the titles and authors of the 41 papers presented at the Stability and Control Meeting held in Brussels in April, 1960, together with the AGARD Report number covering the publication of each paper.

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